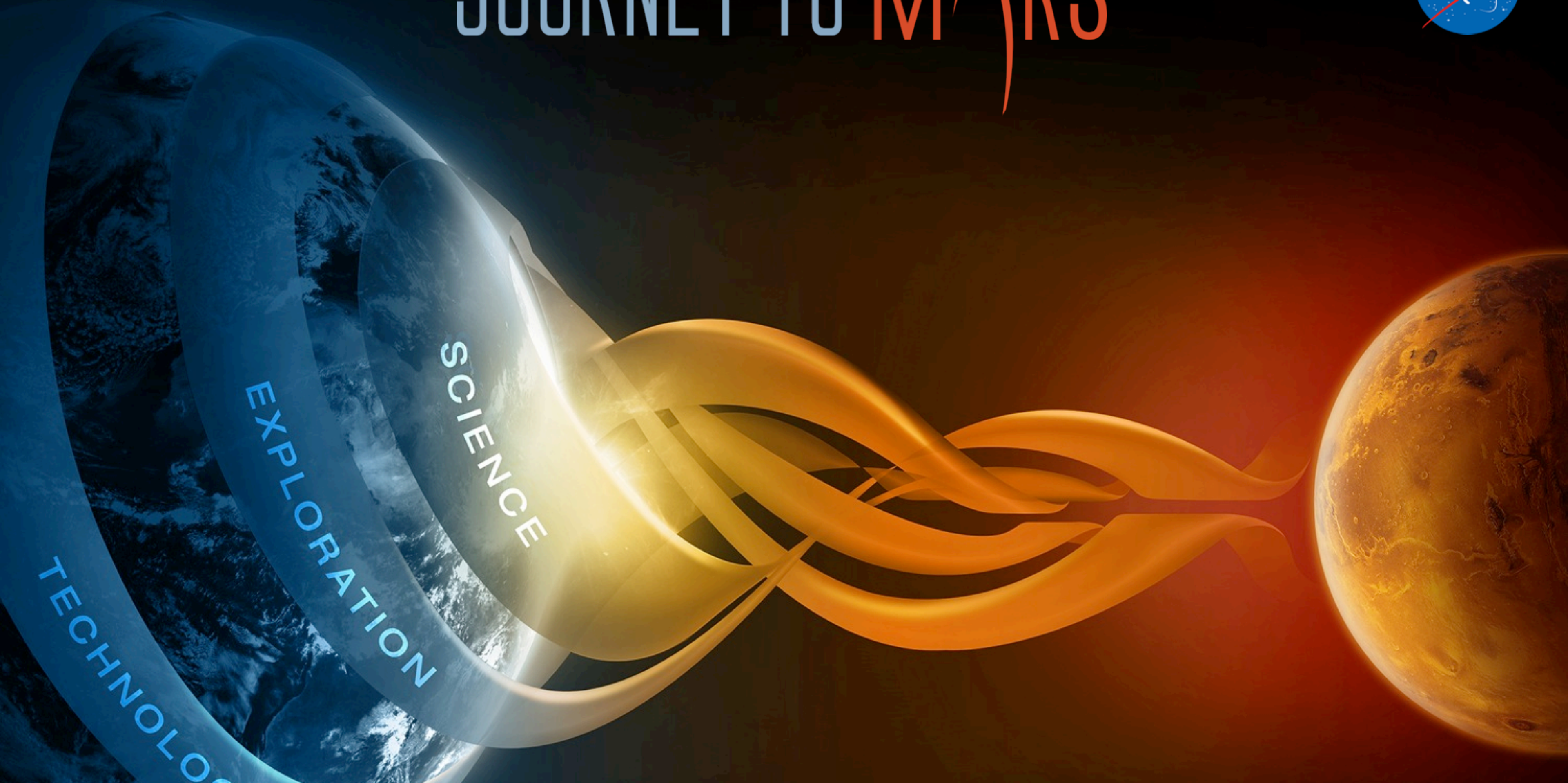
JOURNEY TO MARS

NASA



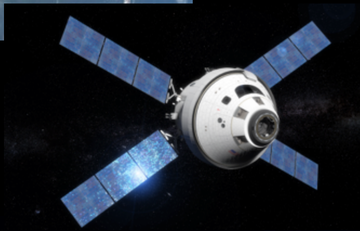
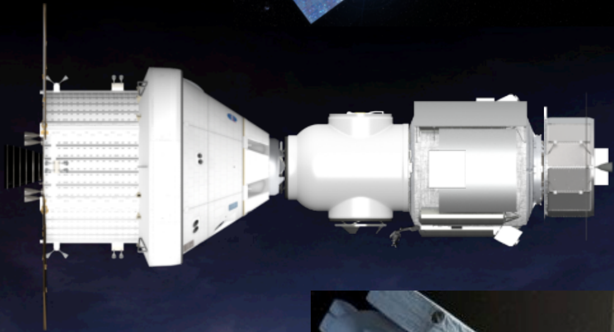
Asteroid Redirect Mission Update

NAC HEO Committee

January 13, 2015

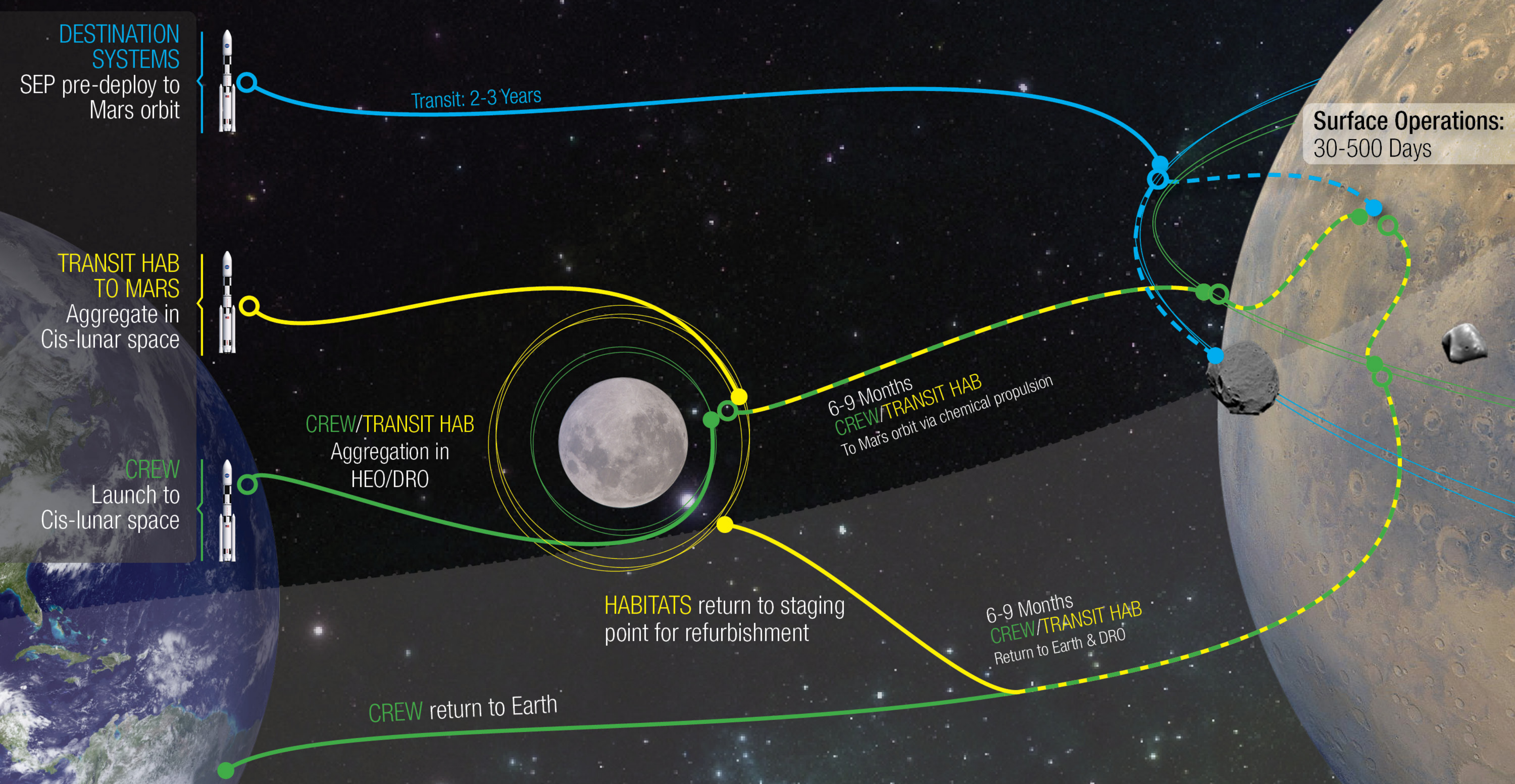
Proving Ground Objectives Enable Mars Missions

- **Demonstrate SLS and Orion in deep space**
  - Critical Mission Events
    - Separation Events, Key Maneuvers, Re-entry, Landing and Recovery
  - Co-manifested cargo capability with Orion, including loads, dynamics.
  - Demonstrate integrated vehicle systems in flight
    - Deep space communications, power and thermal systems, in-space maneuvering
  - Validate environments
  - Autonomous operations
- **Demonstrate use of LDRO as a staging point for large cargo masses en route to Mars**
- **Conduct deep-space EVAs with sample handling**
- **Integrated human and robotic mission operations**
- **Evaluate crew health and performance in a deep space environment**
- **Demonstrate advanced Solar Electric Propulsion (SEP) systems to move large masses in interplanetary space**
- **Demonstration of In-Situ Resource Utilization in micro-g**
- **Learn to operate with reduced logistics capability**
- **Demonstrate long duration, deep space habitation systems**
- **Demonstrate structures & mechanisms**
  - Low temperature and mechanisms for long duration, deep space missions
  - Inflatable structures

Split Mission Concept

Getting to Mars



Returning to Earth

- Returning from Mars, the crew will return to Earth in Orion and the Mars Transit Habitat will return to the staging point in cis-lunar space for refurbishment for future missions

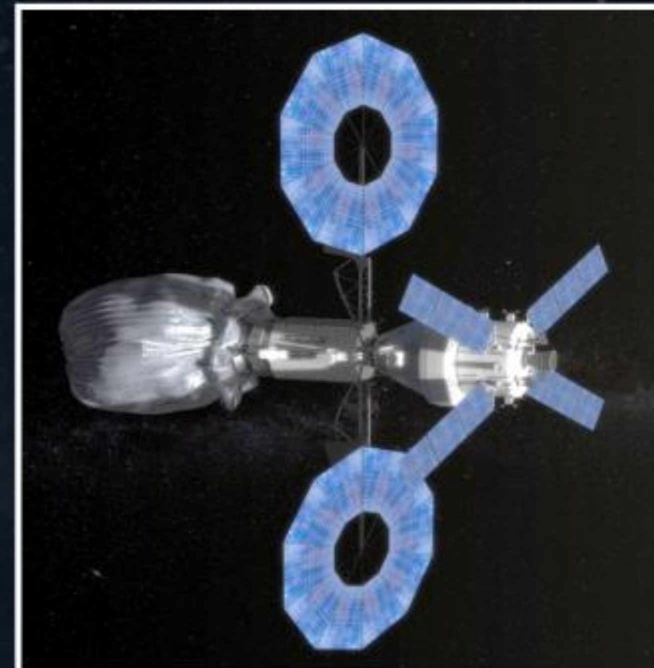
Key ARM Contributions in the HSF Proving Ground

- **Moving large objects through interplanetary space high-powered, long-life SEP**
- **Placing a large object into lunar orbit provides direct design and operations experience in moving large masses, such as Mars cargo.**
- **Use of the lunar distant retrograde orbit for staging point**
- **Integrated crewed/robotic vehicle stack operations beyond low Earth orbit**
  - Integrated attitude control, e.g. solar alignment
  - Multi-hour EVAs
  - SEP vehicle can provide power for future missions
- **In-space EVAs; sample selection handling and containment**
- **Integrates robotic mission and human space flight (HSF) capabilities**
  - HSF hardware deliveries to and integration and test with robotic spacecraft
  - Joint robotic spacecraft and HSF mission operations

Asteroid Redirect Crewed Mission Overview

Deliver Crew on SLS and Orion

Orion Travels To and Docks with Robotic Spacecraft

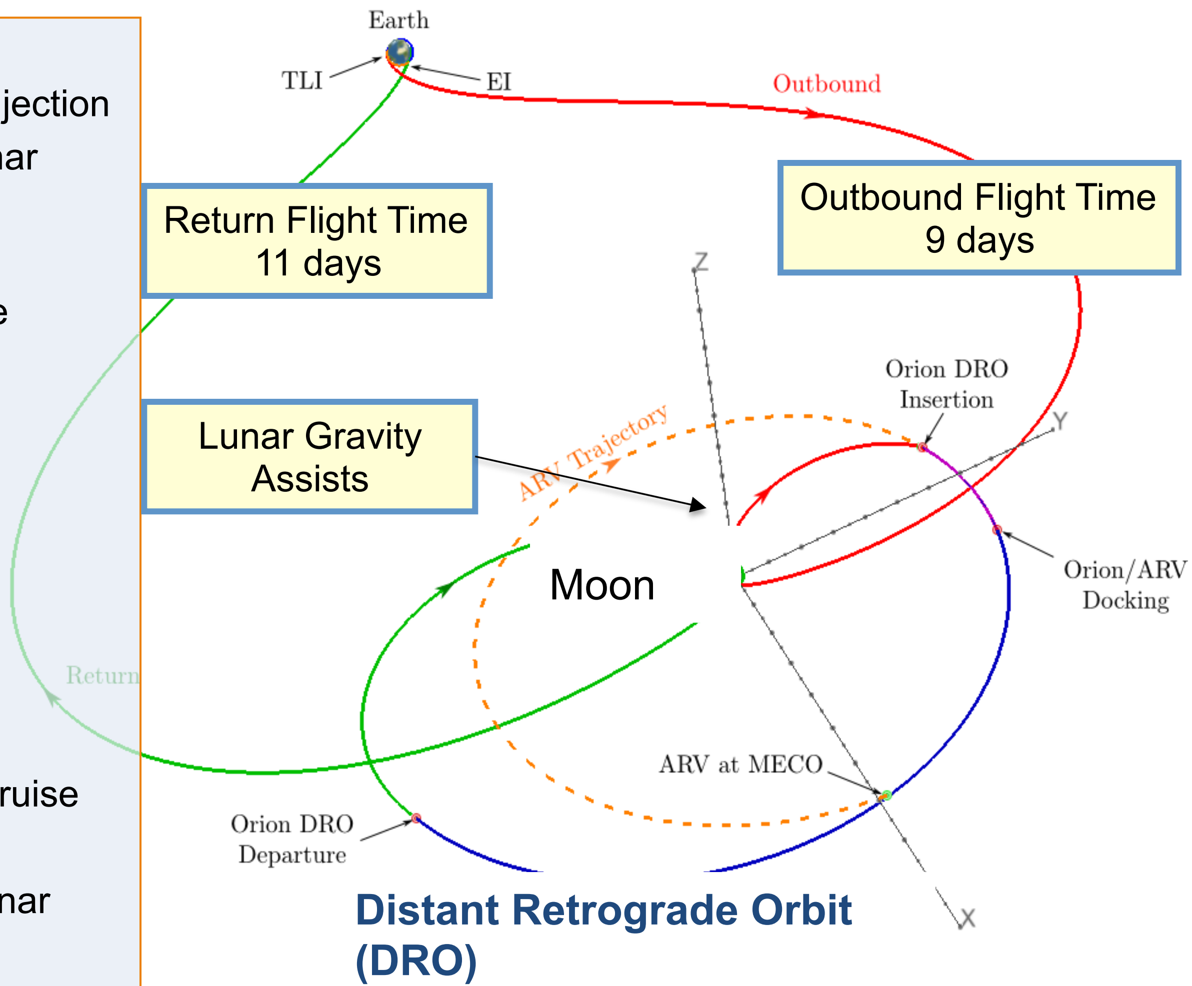


Perform extra-vehicular activity to retrieve asteroid samples

Return crew safely to Earth with asteroid samples in Orion

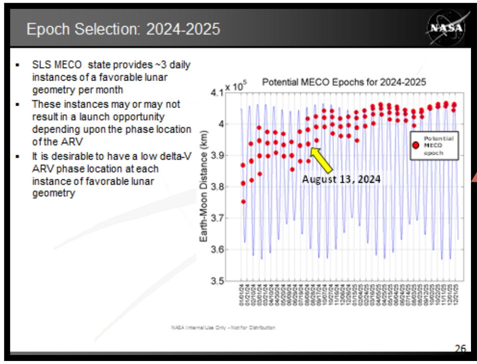
Reference Trajectory: Earliest Mission for 2009BD

- Outbound
  - Flight Day 1 – Launch/Trans Lunar Injection
  - Flight Day 1-7 – Outbound Trans-Lunar Cruise
  - Flight Day 7 – Lunar Gravity Assist
  - Flight Day 7-9 – Lunar to DRO Cruise
- Joint Operations
  - Flight Day 9-10 – Rendezvous
  - Flight Day 11 – EVA #1
  - Flight Day 12 – EVA #2 Prep
  - Flight Day 13 – EVA #2
  - Flight Day 14 – Departure Prep
  - Flight Day 15 – Departure
- Inbound
  - Flight Day 15 – 20 – DRO to Lunar Cruise
  - Flight Day 20 – Lunar Gravity Assist
  - Flight Day 20-26 – Inbound Trans-Lunar Cruise
  - Flight Day 26 – Earth Entry and Recovery



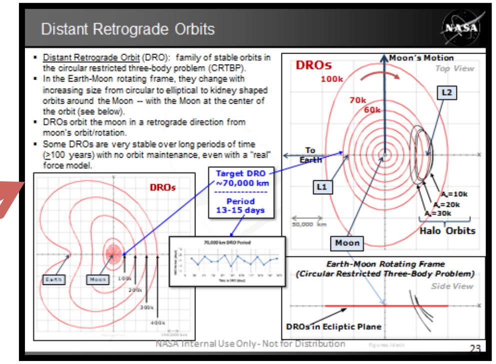
Mission Duration and timing of specific events will vary slightly based on launch date

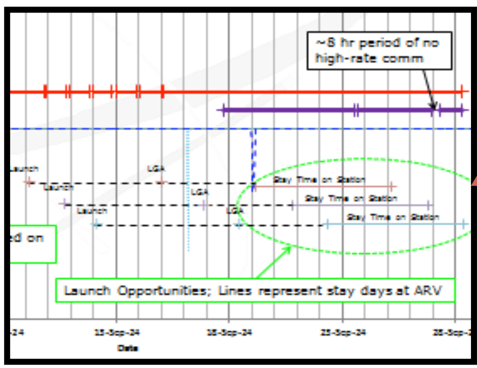
Crewed Mission Design Considerations



Launch Availability ~2-3 opportunities per month

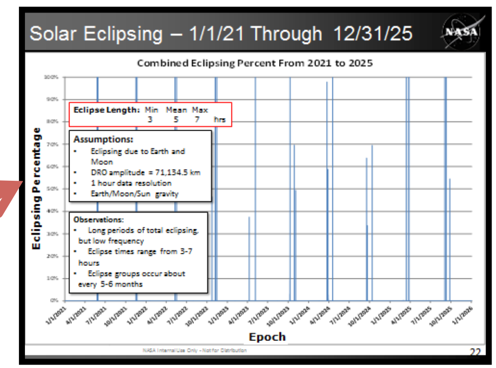
71433km DRO improves launch availability by syncing with Lunar period

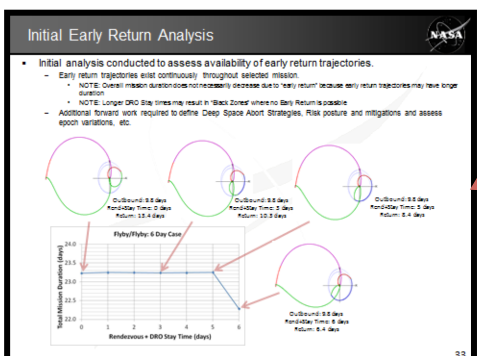




Acceptable Communications Coverage for Orion/ARRV

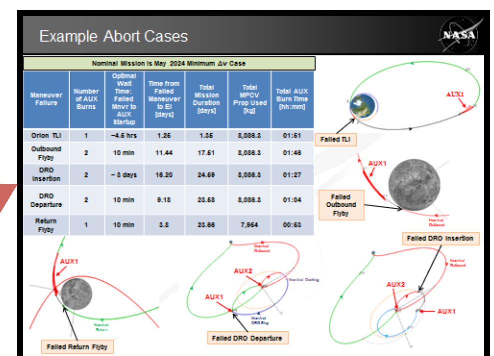
Long Solar Eclipse Periods Manageable for launch availability





Orion Propellant Available for Early Return Throughout Mission

Orion Propellant Allows Auxiliary Thruster Contingency Return



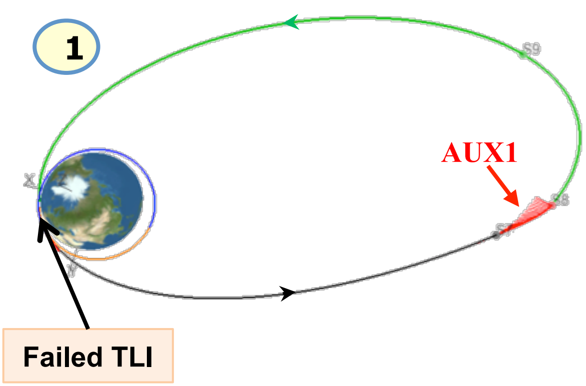
Contingency Trajectory Planning

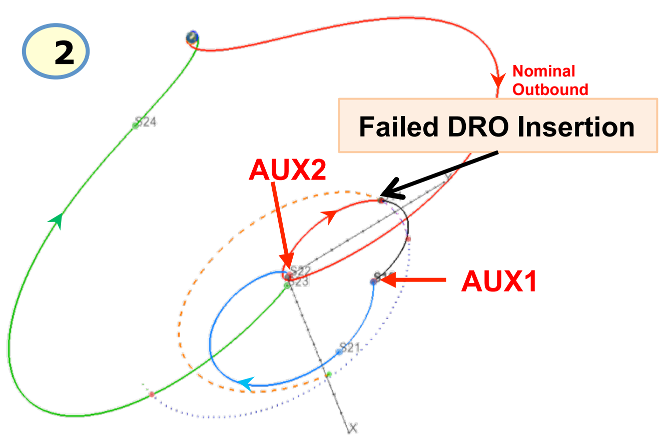
MFR Reference Mission: May 2024, Min-ΔV

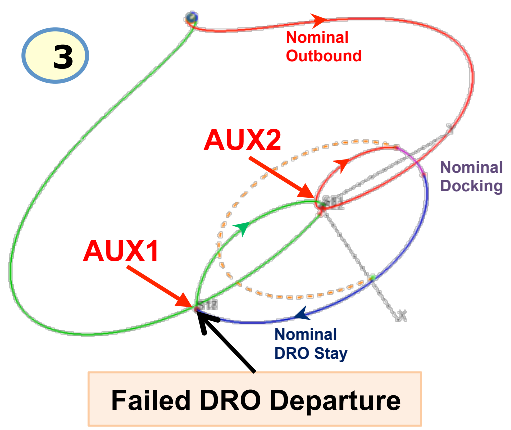
Maneuver Failure (DD:HH:MM)	Number of Aux Burns	Total Mission Duration [days]
Orion TLI (0/02:00)	1 (1)	1.36
Outbound Flyby (6/01:36)	2	17.57
DRO Insertion (8/06:47)	2 (2)	26.69
DRO Departure (14/06:51)	2 (3)	23.61
Return Flyby (19/19:31)	1	23.66

- Nominal Mission Duration is 25 days 17 hours
- Examined failure of Service Module (SM) Main Engine throughout mission
- Orion SM contains substantial additional propellant above the nominal mission requirement and 30 days of crew consumables (O2, N2, food, etc.)
- Assessment concluded that Auxiliary Thrusters could complete the mission should SM Main engine fail although mission duration may be longer than nominal mission
- All usable Orion Propellant burned in Abort Cases to minimize return duration

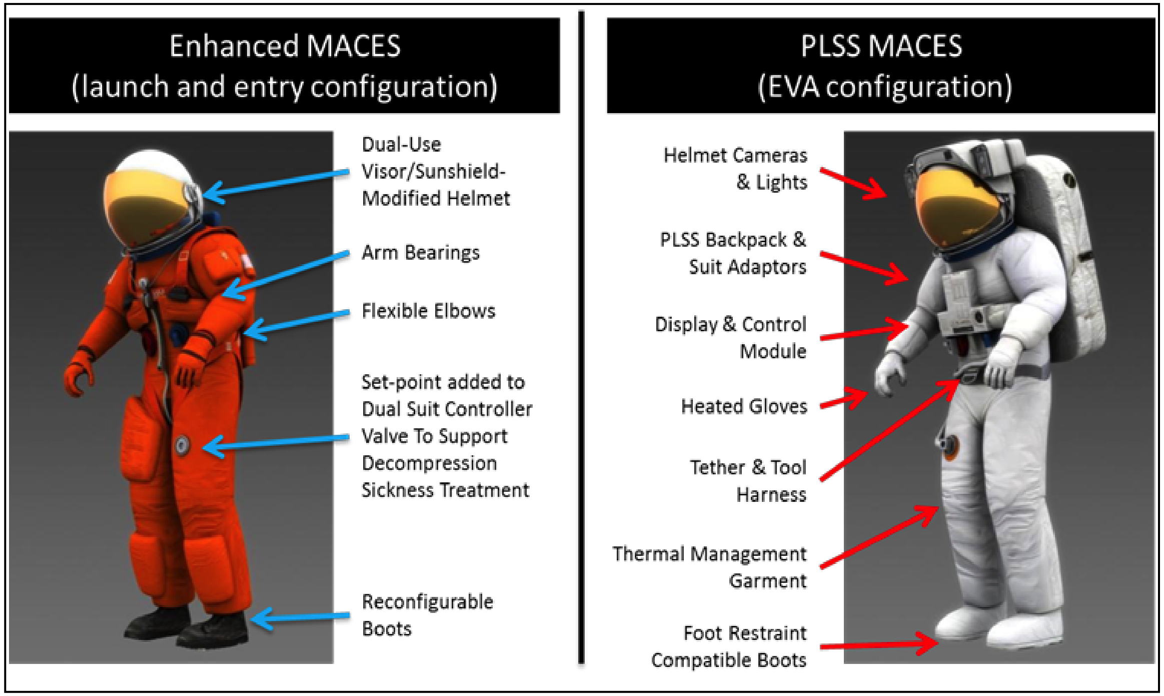
Example Failed Maneuvers followed by Auxiliary Engine Maneuvers





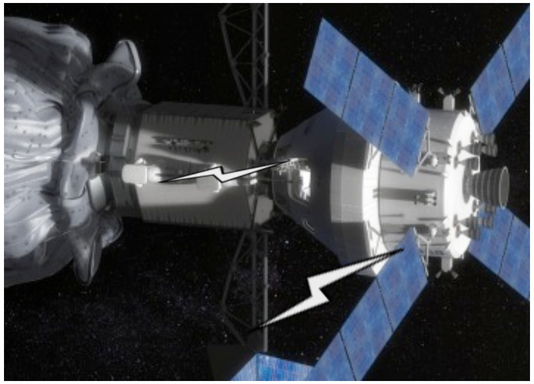


Mission Kit Concept Enables Affordable Crewed Mission

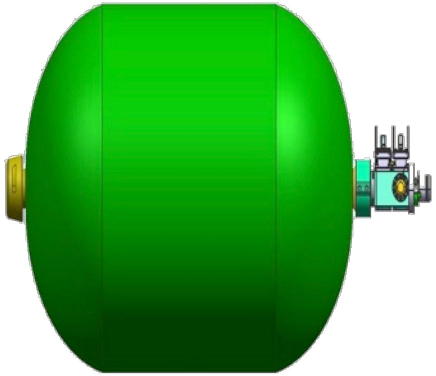


Tools & Translation Aids

Sample Container Kit



EVA Communications Kit

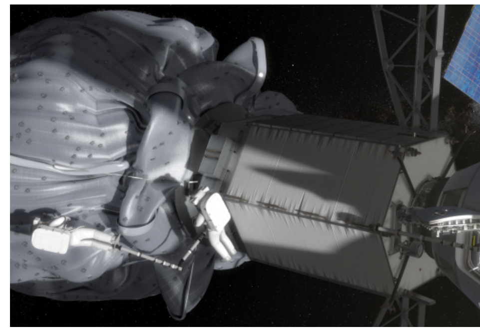


Repress Kit

Most hardware needed for other exploration missions

Suit and EVA Mission Kits

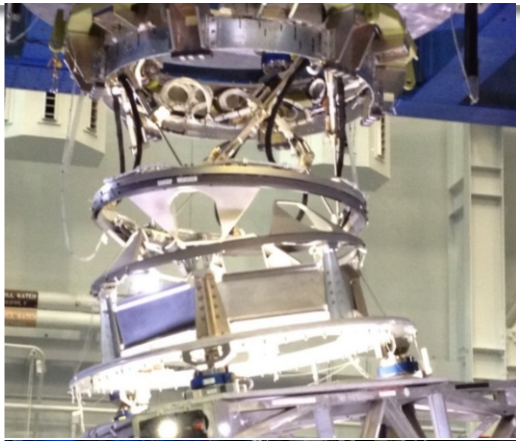
Four kits were identified to enable Orion Capsule-Based EVA capability

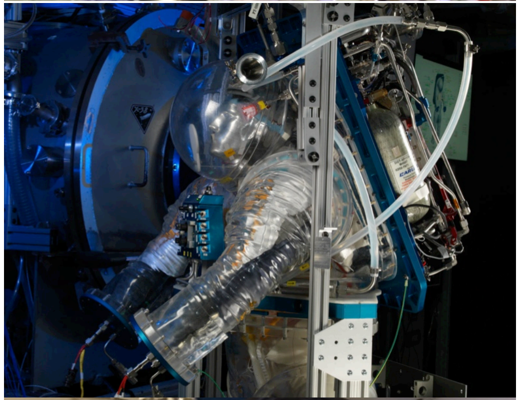


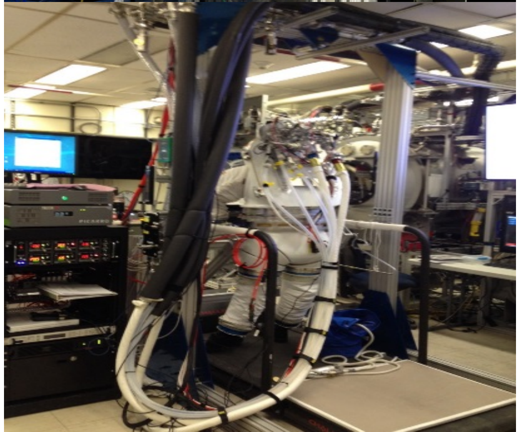
EVA Servicing and Recharge	EVA Tools, Translation Aids & Sample Container Kit	EVA Communications	Cabin Repress Kit
Equipment necessary for multiple EVAs including recharge for PLSS water and oxygen, crew equipment, etc.	Standard and specialized tools to complete mission objectives	Repackaged PLSS radio that allows relay communication between EVA crew and ground	Provides enriched air for multiple repressurizations of the cabin without using Orion resources
Based on ISS and Shuttle equipment	Leverage current ISS, heritage Apollo and analog tools; Evaluate prototype designs in NBL	Utilizes common radio design currently being developed for AES PLSS	Based on ISS tanks; Plan to mature concept in work

ARM Crewed Mission Progress in 2014

- Developed Common AR&D Specifications
  - BAA Awarded to Ball Aerospace and Boeing
- Significant Progress on NASA Docking System Block I
  - 90+% drawings have been released in CDR Phase
  - Component development testing underway
  - Successful 6 Degree of Freedom testing at JSC for a wide variety of contact conditions and vehicle masses
- Completed PLSS 2.0 integrated testing primary objectives
  - Full integrated test system with human metabolic simulator
  - Integrated system performed as designed
- AES PLSS 2.0/Mark-III Suit Human-in-the-Loop Testing
  - Completed 60 hours of cumulative test time, including more than 37 hours of metabolic rate profile data.
  - Six test subjects, three metabolic rate profiles, two Liquid Cooling and Ventilation Garments, Aux and Prime PLSS thermal loops (Primary and Auxiliary)
  - Assessed fan noise, RCA cycling, moisture, air-flow
- Completed four additional MACES NBL Runs to evaluate EVA techniques and test MACES mobility
- Completed extensibility study for SEP as part of Evolvable Mars Campaign



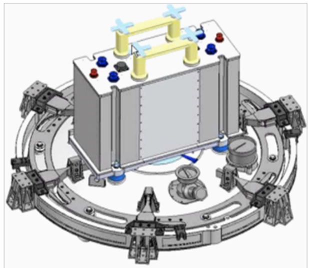




Automated Rendezvous and Docking Common Specification

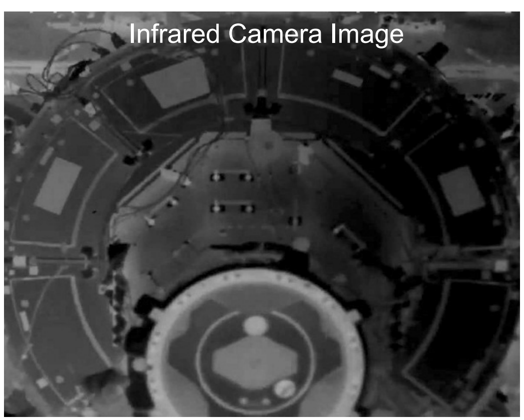
- Common Specification developed after detailed study of robotic and crewed mission Concepts of Operations
  - Visible cameras (medium resolution and high resolution)
  - 3D LIDAR
  - Infrared camera for robustness/situational awareness
- BAA contracts awarded to Boeing and Ball Aerospace
  - Interim Reviews completed in November 2014 with significant design progress and risk reduction work performed
  - Final reports in January 2015

Orion Packaging of Common AR&D Sensors

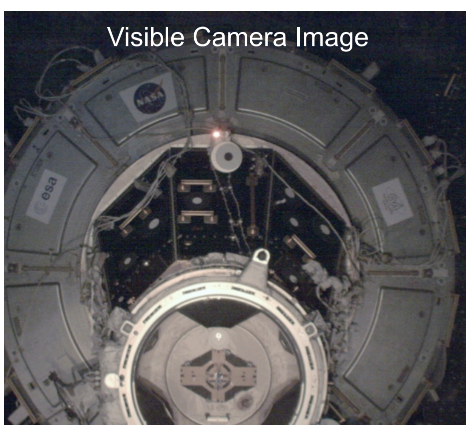


Relative Navigation Sensor Kit

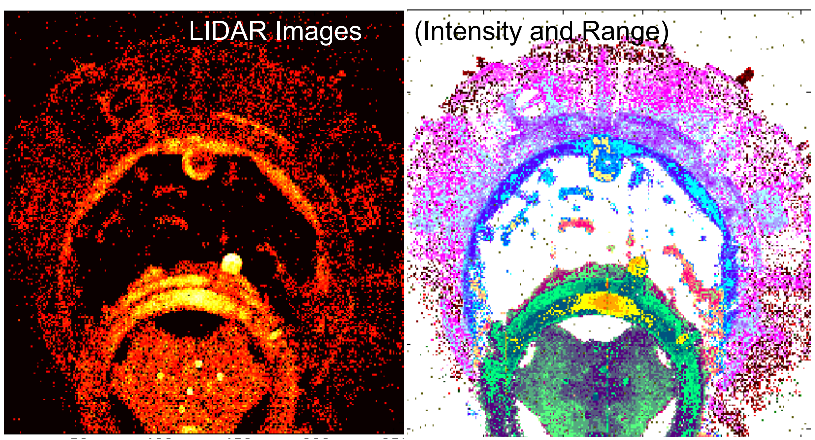
	Common AR&D Suite Application to Asteroid Missions		
	Robotic Small Asteroid Capture	**Robotic Boulder off Large Asteroid**	**Crewed**
Visible Cameras	Medium Res	2 Medium Res, High Res	High Res
All **3D LIDAR**	Yes	Yes	Yes



Infrared Camera Image



Visible Camera Image



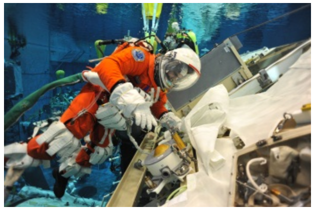
LIDAR Images (Intensity and Range)

Modified ACES Suit Feasibility Testing Summary

Lab, Zero G, ARGOS tests

MACES EVAs are demonstrated as feasible and neutrally buoyant testing is warranted

NBL Series #2 – 5 tests (2, 3 and 4 hours long)



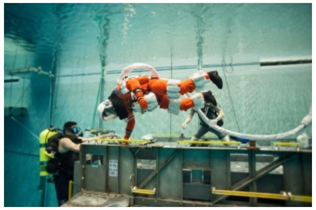
Task complexity increases while improvements are made to the suit including EMU gloves, drink bag, etc.

Need for improved stability and work envelope

Initial NBL testing has shown feasibility of doing many asteroid retrieval sampling tasks using a MACES. Continued testing with a variety of crew member sizes, along with incremental suit and tool enhancements is critical in order to validate the concept.

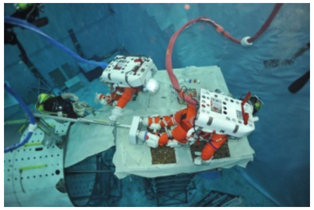
May | June | July | August | Sept | Oct – Jan | February | March | April | May

NBL Series #1 – 3 tests (2 hours long)



Established NBL Interface, ability to weigh-out the suit, and the subject's ability to use the suit underwater.

NBL Series #3 – 5 tests (4 hours long)

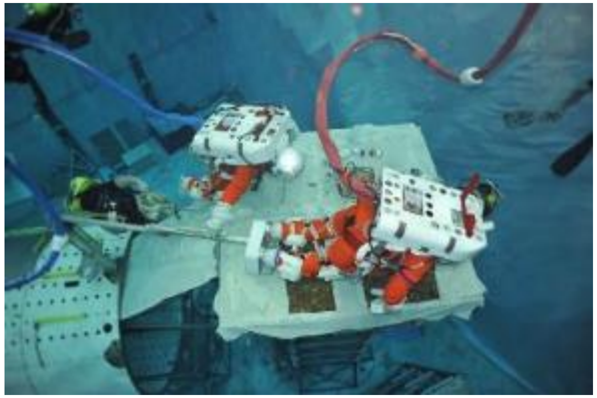


Evaluation of mobility enhancements, improved worksite stability, and testing on higher fidelity capsule mockups with tools culminating in a full ARCM EVA timeline.

Hardware and Procedure Improvements

- Improved weights
- EMU Gloves
- Added tool harness
- Drink bag included
- New liquid cooling garment
- Mobility Enhancements
- Dual Suit Ops
- EMU Boots
- PLSS Mockup
- Body Restraint Tether

NBL Test Results – Worksite Stabilization



- Adjustable Portable Foot Restraint operations were tested and execution is very similar to the ISS Extravehicular Mobility Unit.

- Body Restraint Tether allowed the crew to perform two handed tasks

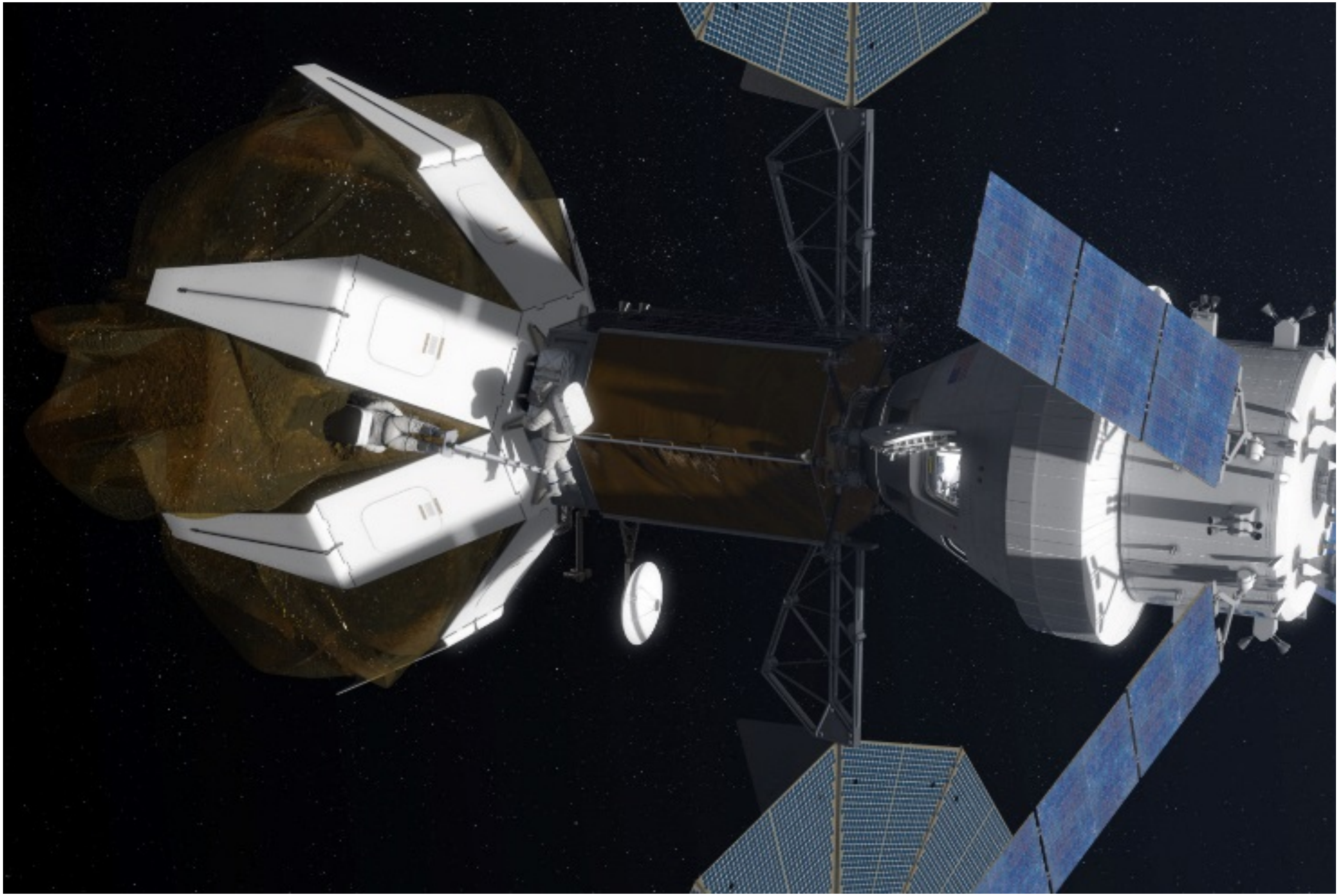
- Crew was able to perform several sampling tasks including worksite imaging, float sample collection, hammer chiseling and pneumatic chiseling.

ARM Crewed Mission Assessment of Option A/B

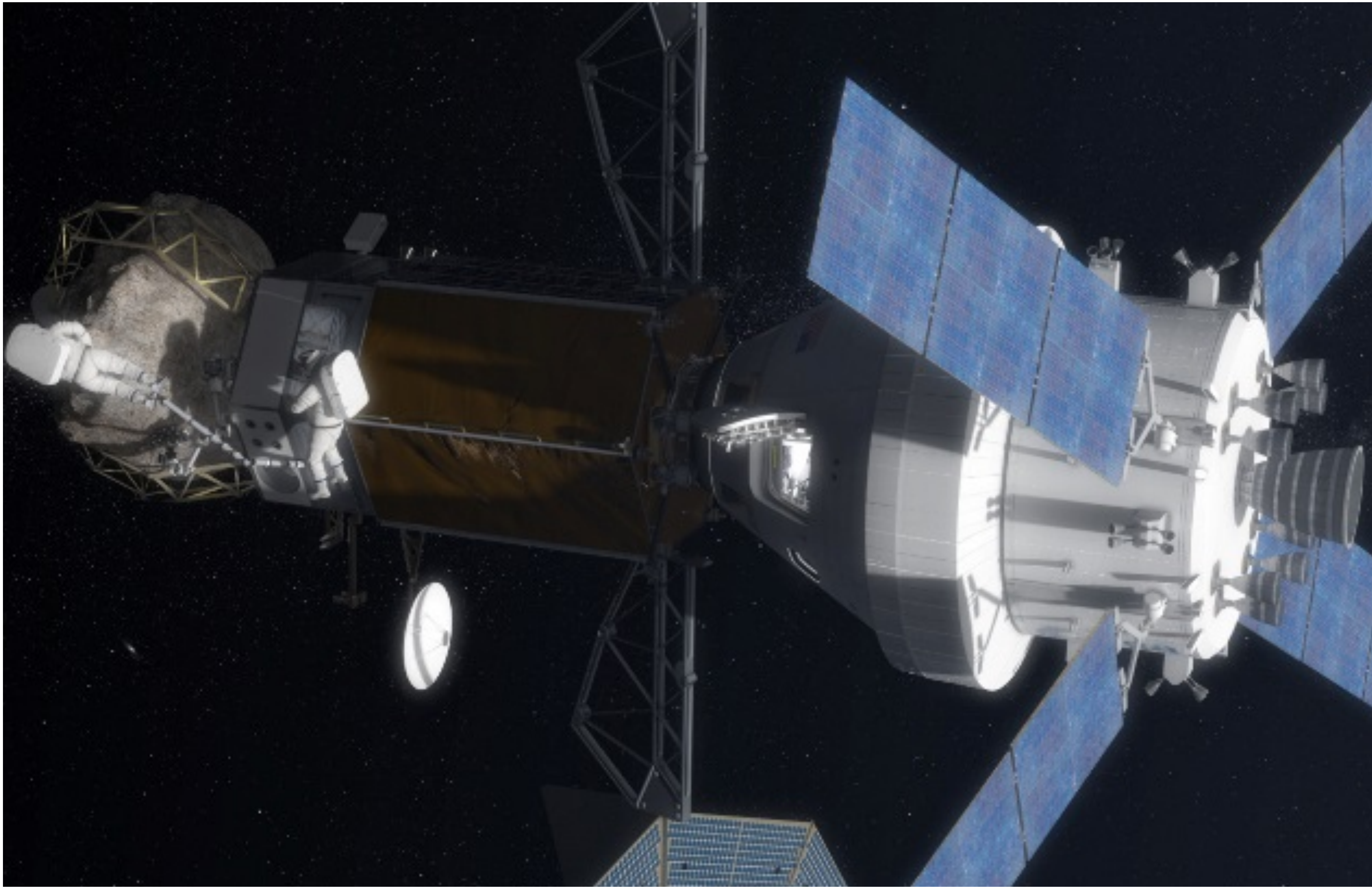
- **As part of the assessment, the JSC team evaluated each mission phase and determined EVA is the only phase with significant differences between the capture options.**

Mission Phase	Option A and Option B Comparison
Orion Launch to Rendezvous	Not a discriminator between Option A and B
Orion Rendezvous, Proximity Operations, and Docking with ARV	Design Considerations for Integrated Stack mass properties: • Option A asteroid can be heavier than Option B Boulder • Docking loads impart different attitude excursion, however, Orion can arrest rates and return stack to nominal attitude in either option.
Joint Operations	
- Integrated Attitude Control	Orion can maneuver integrated stack for either option. Mass is higher for Option A for complete range of asteroid sizes.
- EVA	Either Option is Acceptable (Small diameter asteroid/boulder require special considerations-discussed in later slides). Cutting through Option A bag has been demonstrated in NBL.
Orion Return to Earth	Not a discriminator between Option A and Option B

Option A EVA Concept



Option B EVA Concept



Curation and Planning Team for Extraterrestrial Materials

Curation and Planning Team for Extraterrestrial Materials (CAPTEM) recommendations provided for:

- Activities conducted during EVAs that are relevant for characterization, selection, collection, stowage, and transport of multiple samples to Earth.
- Tool/instrument protocols relevant for sample collection and characterization.
- High level objectives required to maximize the scientific usefulness of the EVAs and ensure the scientific integrity of the returned samples.

Key Findings:

1. Sampling site contamination control is vitally important.
2. Contamination control is important across all stages of mission.
3. Scientific return is likely maximized by picking option that presents least risk of contamination.
4. Assessment of textural and mineralogical heterogeneity of body is critically important.
5. Active participation of ground-based Science Team is critically important.
6. Hand-held high-resolution cameras and analytical instruments is valuable during EVA.
7. Collection of at least 1000g from two diverse sites is recommended.
8. If practical, collection from at least one 5-cm diameter core sample.
9. Preservation of volatiles is desirable (<20°C)
10. Surveying tools on the surface could assess deformation of body.
11. Optical albedo measurements and measurements of the Yarkovsky effect are not of high priority.

Comparison of Option A and B:

Commonality exists in various areas of both options. In aggregate Option A provides limited situational awareness due to obstructed view from petals and bags while Option B provides superior situational awareness and access for crew due to open spaceframe CRS legs. (see backup CAPTEM Finding Tables).

Performance of ARM SEP spacecraft after ARM mission

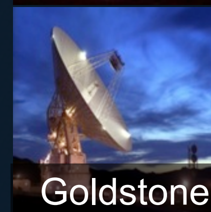
- ARM robotic vehicle reference design can provide the following capabilities for docked vehicles:
  - ~40 kW of power at TBD voltage (currently 300 V unregulated)
  - A two way data interface through the FRAM* connector for a docked element
  - S-Band transponder, useful for approach/docking
  - X-Band comm link allowing downlink or uplink of docked element data
  - A passive docking mechanism compliant with the International Docking Standard
  - Coarse attitude control to maintain power and thermal constraints of the ARV vehicle when Orion is not docked
  - Four 13 kW Hall thrusters, three of which will be operated in parallel to provide approximately 40 kW of SEP at 1 AU, limited by how much xenon propellant remaining in the tanks
  - Various tools for EVA

* Flight Releasable Attachment Mechanism

Asteroid Redirect Mission: Three Main Segments

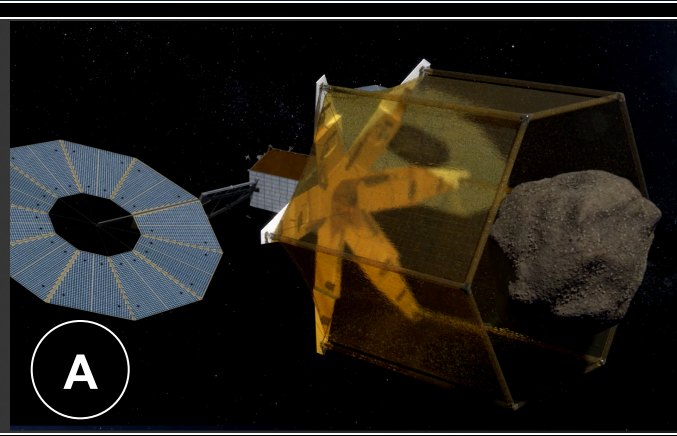
IDENTIFY

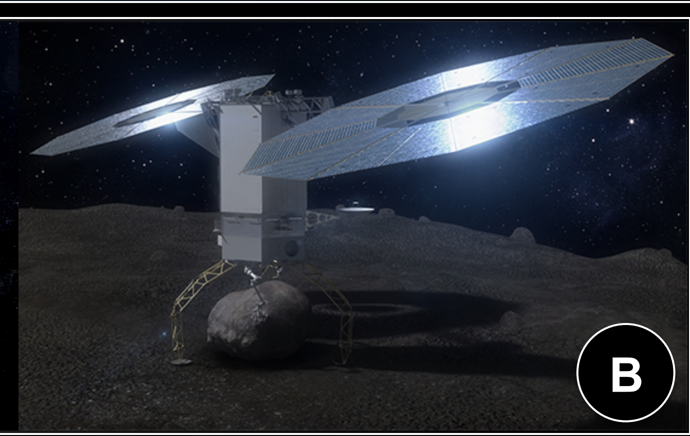
Ground and space based assets detect and characterize potential target asteroids



REDIRECT

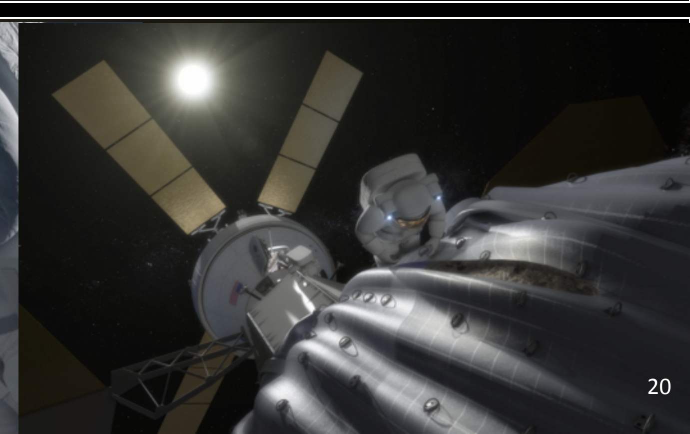
Solar electric propulsion (SEP) based system redirects asteroid to cis-lunar space (two capture options)





EXPLORE

Crews launches aboard SLS rocket, travels to redirected asteroid in Orion spacecraft to rendezvous with redirected asteroid, studies and returns samples to Earth



Accomplishments since July 2014 (1)

- **Enhanced asteroid observations underway with new asteroids identified**
  - Enhanced NEA characterization techniques have been tested, validated and implemented.
    - Rapid Response by IRTF and interplanetary radars (Goldstone and Arecibo)
    - Improved resolution by radar imaging (~8 meters reduced to <4 meters)
    - Use of Spitzer to determine size and rough mass, density, composition of very dim candidates.
    - No new valid candidates identified as of yet
- **Advanced solar electric propulsion technology development and testing completed**
  - Solar arrays, Hall thrusters, power processing units operating at several voltages and power levels
- **Broader engagement through the Curation and Analysis Planning Team for Extra-terrestrial Materials and Expert and Citizen Assessment of Science & Technology**

Accomplishments since July 2014 (2)

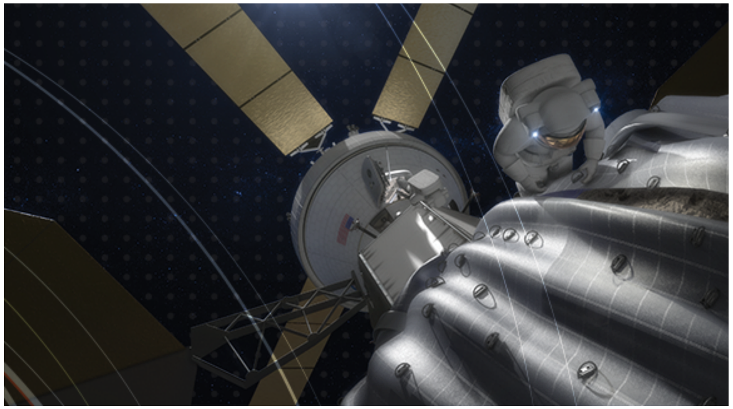
- **Interim reports received for 18 study contracts; selections through Broad Agency Announcement. Final reviews by end of January.**
  - Capture systems
  - Common rendezvous sensor suite
  - Leveraging commercially available spacecraft for robotic mission
  - Partnerships in secondary payloads for robotic mission
  - Partnerships for crewed mission including extensibility
- **Internal design and risk reduction activities to mitigate risk in the capture phase**
  - Option A
    - Higher fidelity 1/5 scale testbed
    - Revised the design
    - Conducted testing of deployment/inflation, “docking” to the asteroid, and bag closure, with force measurements
    - Friction tests using prototype bag material
  - Option B
    - Full scale testbeds
    - Capture arm & tool testing and force measurements; extraction force testing
    - Contact & restraint 2D testing and force measurements
    - Closed loop sims of descent, surface ops and ascent w/ADAMS & structural/thermal analysis
    - Sensor and algorithm testing to validate relative navigation approach
    - Extraction option pull tests

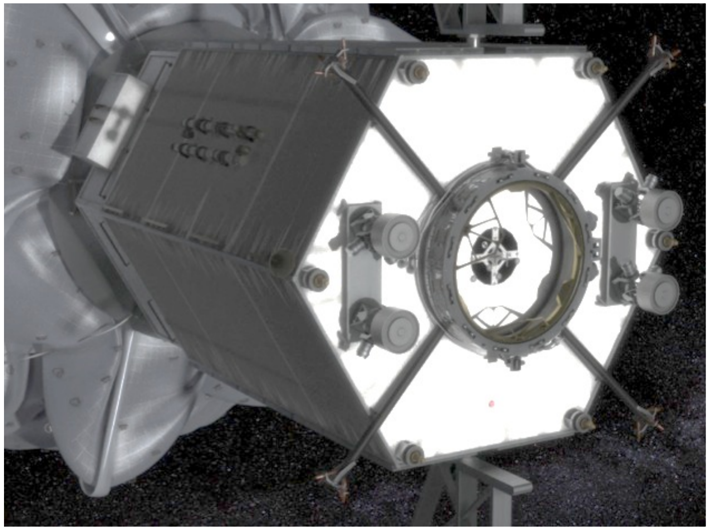
Accomplishments since July 2014 (3)

- **Robotic mission architectures and mission designs**
- **Updated cost and schedule grass roots estimates for reference launch date June 2019; variations**
- **Initiated independent technical and cost assessment for MCR**
  - Relative comparison for capture mission options provided for capture mission downselect
- **Identified applications of ARM technologies, systems, and operations extensibility to future crewed missions**
  - ISS Capability Development Study
  - Evolvable Mars Campaign
- **Continued to evaluate common Automated Rendezvous and Docking sensor approach for robotic spacecraft and crewed mission**
- **Continued prototyping and testing to gain confidence that there is a path to use Orion launch and entry suit derived from the modified advanced crew escape suit (MACES) for these in-space EVAs**
  - Testing in Neutral Buoyancy Lab
- **Conducted robotic capture mission downselect review (Option A/Option B)**

Current Objectives of Asteroid Redirect Mission

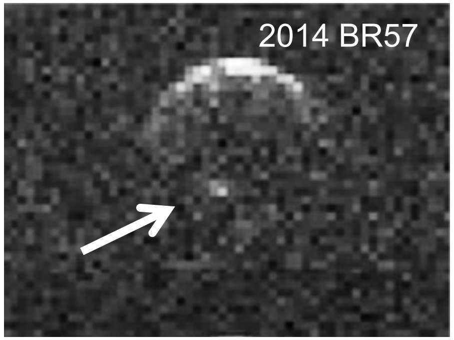
- **Conduct a human exploration mission to an asteroid in the mid-2020's, providing systems and operational experience required for human exploration of Mars.**
- **Demonstrate an advanced solar electric propulsion system, enabling future deep-space human and robotic exploration with applicability to the nation's public and private sector space needs.**
- Enhance detection, tracking and characterization of Near Earth Asteroids, enabling an overall strategy to defend our home planet.
- Demonstrate basic planetary defense techniques that will inform impact threat mitigation strategies to defend our home planet.
- Pursue a target of opportunity that benefits scientific and partnership interests, expanding our knowledge of small celestial bodies and enabling the mining of asteroid resources for commercial and exploration needs.

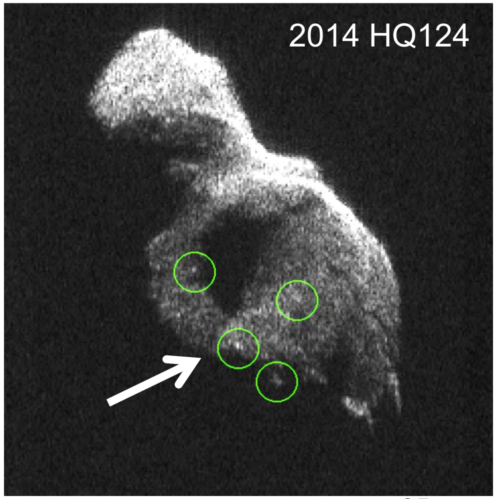




Summary of NEO Radar Observations in 2014

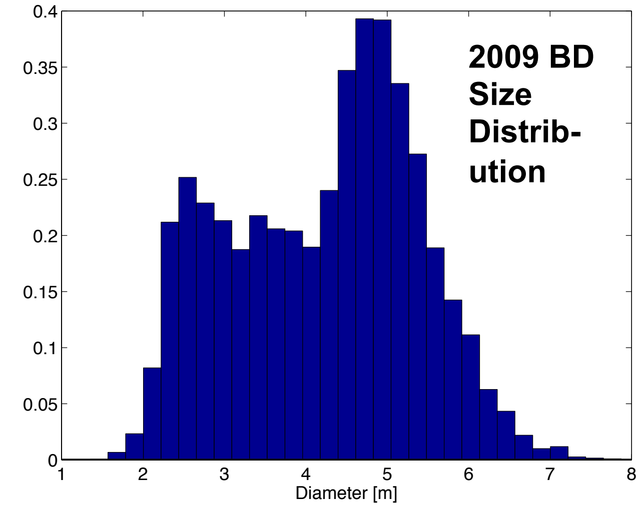
- 88 NEAs and 2 comets were observed by radar in 2014, up 13% from 2013, and more than in any previous year
- This is remarkable considering Arecibo was down for ~120 days due to equipment problems mainly due to damage from an earthquake, and Goldstone was down for ~35 days
- In just the last 2 weeks, Arecibo characterized two ~10m NEAs that were almost suitable candidates for ARM Option A
- 14 NHATS targets were observed by radar this year
- Boulders were detected on two 100m-class NEAs this year, but neither of them was in suitable orbit to be candidate for Option B

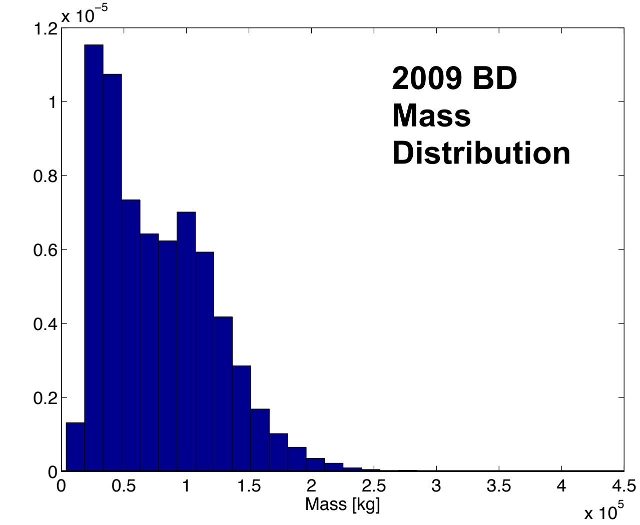




Characterization of Option A Candidates

- **2009 BD and 2011 MD:**
  - Both objects very well observed from the ground, and orbits well determined
  - Spitzer detection or non-detection puts bounds on the sizes
    - 2009 BD observation in October 2013
    - 2011 MD observation in February 2014
  - Non-gravitation parameters can be modeled, yielding distributions on size and mass with good constraints on uncertainties
- **2013 EC20:**
  - Less well observed from the ground
  - Detection by Arecibo radar puts bounds on the size
  - Non-grav parameters were not modeled: mass was estimated from size and assumed range of densities



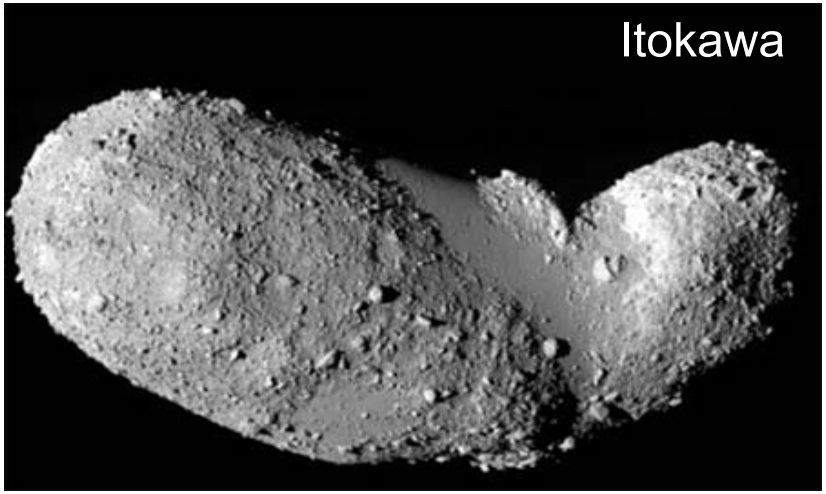


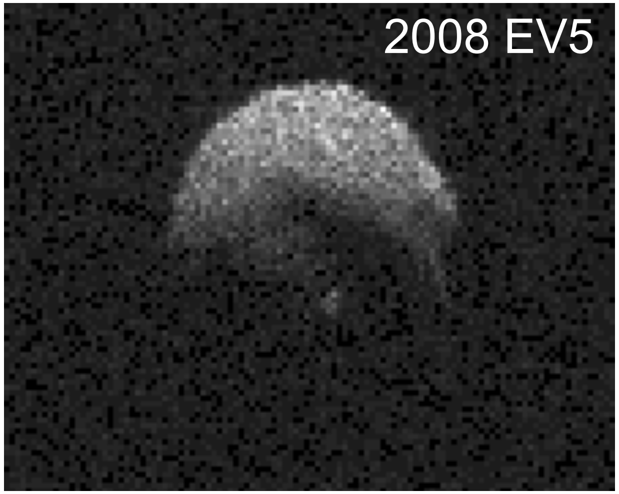
Summary of Option A Candidate Characteristics

Candidate Target	Mass (t)	Size (m)	Spin Period (minutes)
2009 BD 95% upper limit Median 95% lower limit	 157 70 26	 6.0 4.4 2.6	> 180
2011 MD 95% upper limit Median 95% lower limit	 670 110 27	 10.0 6.0 3.1	12
2013 EC20 95% upper limit Median 95% lower limit	 43 20 8	 3.0 2.5 2.0	~2

Candidate Asteroids for Option B

- **Itokawa:**
  - Precursor: Hayabusa in 2005
  - S-type, 535 x 200 m, 12 hr spin
- **Bennu:**
  - Precursor: OSIRIS-REx in 2018
  - B/C-type, 500 m size, 4 hr spin
- **2008 EV5:**
  - No precursor, but radar detected boulders in 2008
  - C-type, 400 m size, 4 hr spin
- **1999 JU3:**
  - Precursor: Hayabusa 2 in 2018/19
  - C-type, 870 m size, 8 hr spin
- **Possible Future Candidates:**
  - No planned precursors, but radar could detect boulders on 2011 UW158 in 2015, 2009 DL46 in 2016



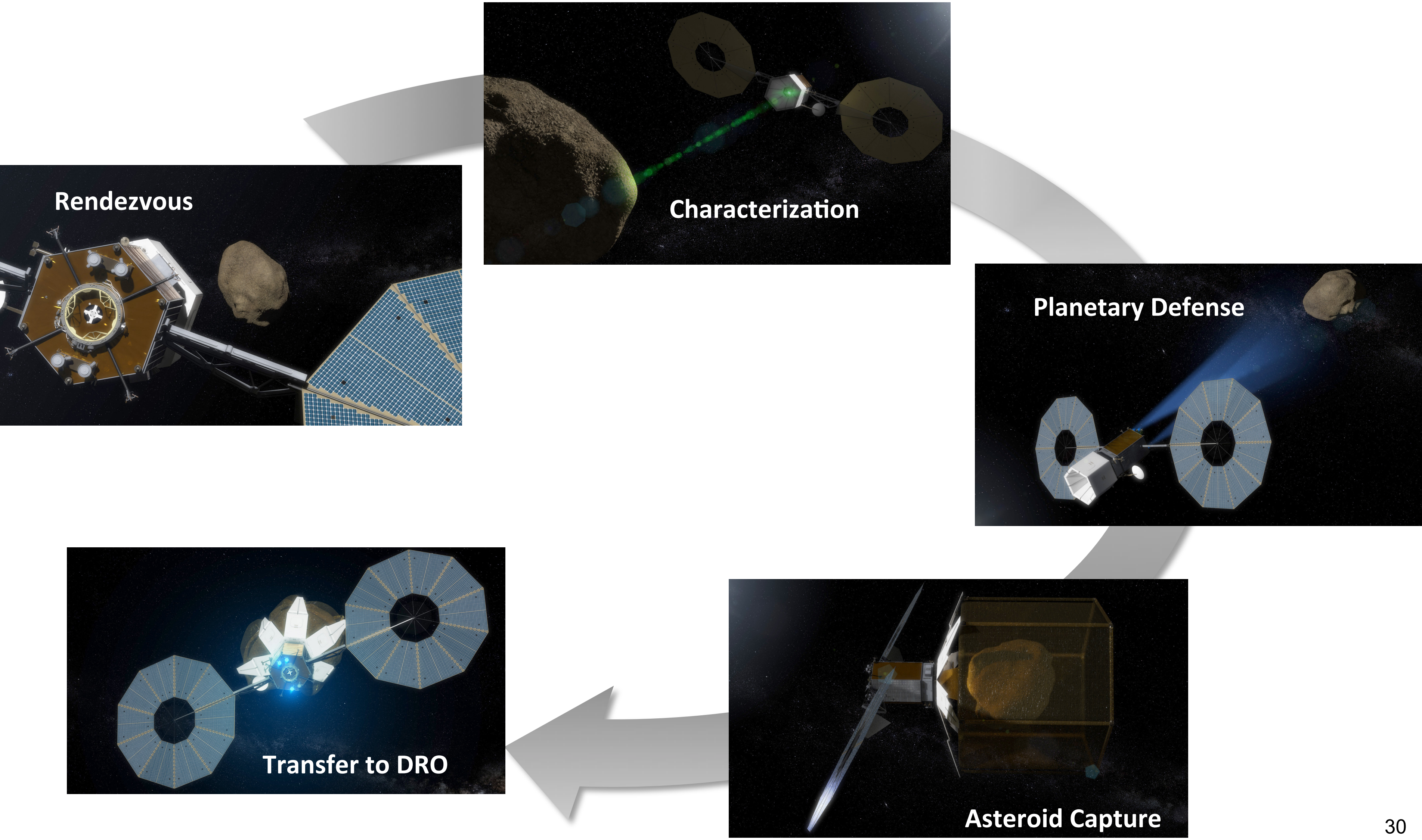


Science Potential

- **SBAG SAT Report**
  - The type of asteroid sampled is of major scientific importance. The Planetary Decadal Survey states that primitive asteroids associated with prebiotic materials (water, carbon, organics) are prioritized for science.
  - Characterizing and returning a sample from an asteroid not already, or planned to be, sampled is of greater science value than characterizing and returning a sample from one that has been.
  - Involvement of a science team is critically important to maximize the science, including during the concept development portion of the mission.
  - Ground-based characterization of the target asteroid is scientifically important.
  - Remote characterization prior to, during, and following sampling provides scientific context.
  - An asteroid sample return mission offers a range of possible science investigations, both with remote characterization and through study of the returned sample.

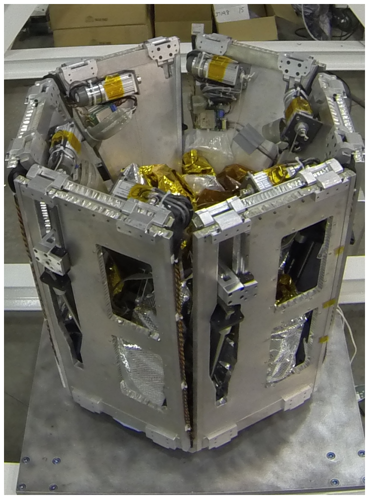
Robotic Capture Mission Option A Overview

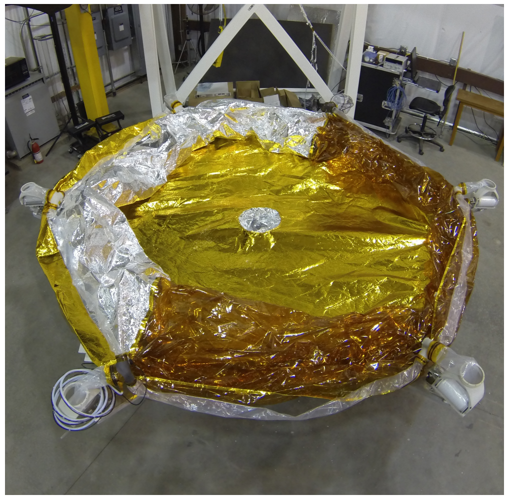
Rendezvous 28 days | Characterization 14 days | Planetary Defense 2 days | 5 days | Asteroid Capture (+30 days margin) | Return to Earth-moon System ~1-3 years



Option A
Analysis and Risk Reduction Overview

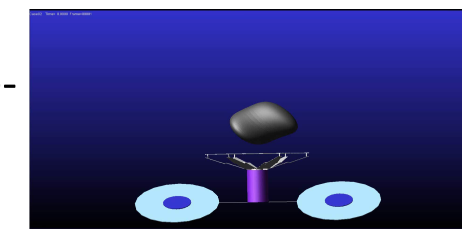
Asteroid Capture Testbed; ADAMS and DARTS/DSHELL simulations



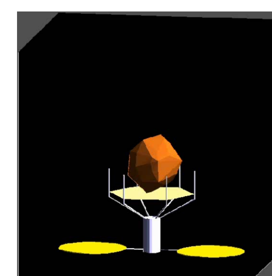


The Asteroid Capture Testbed is a hardware-in-the-loop simulation that measures actual forces between soft goods and asteroid mockup, evolving motion and spin of asteroid per real physics, providing better understanding of soft goods packaging and deployment and defining precisely what force/deflection characteristics are required for the corners of the trampoline to accommodate full range of asteroids while minimizing forces on S/C.

The ADAMS simulation provides high-fidelity finite-element physics giving loads, etc., but slow to compute.

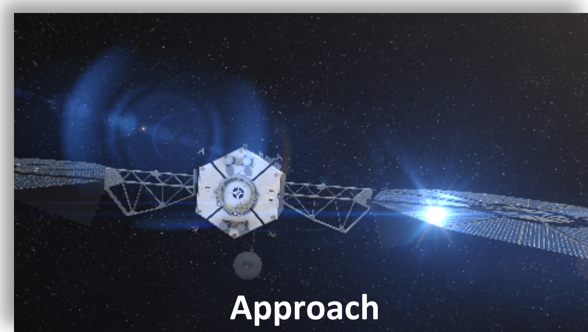


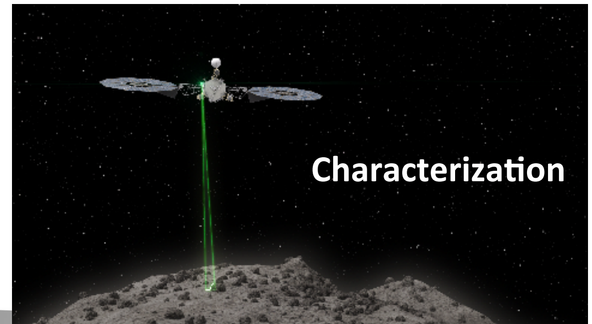
The DARTS/DSHELL simulation is a fast, low-order physics-based model suitable for Monte Carlo and control system modeling.

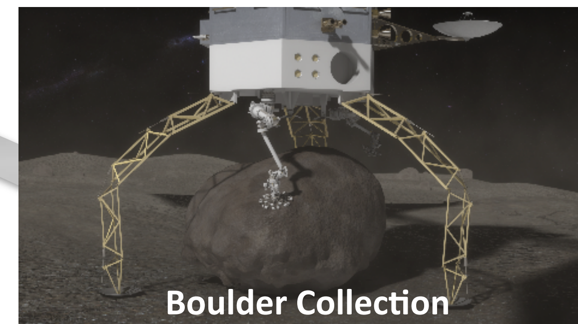


Robotic Capture Mission Option B
Proximity Operations Overview

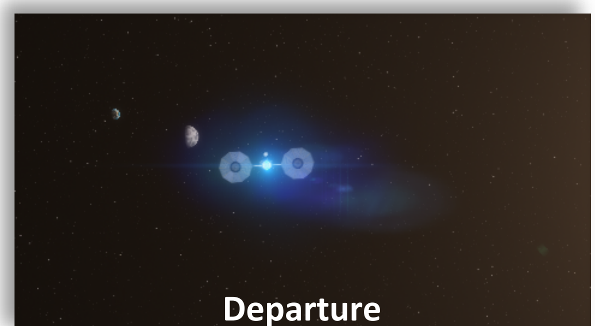
Approach	Characterization	Boulder Collection	Planetary Defense Demo
14 days	72 days	69 days	150 days (30 deflection + 120 hold & verify)



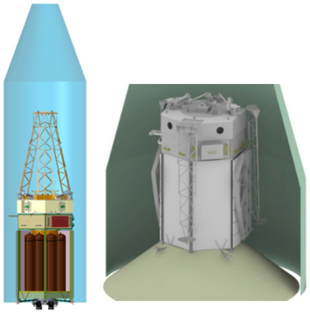




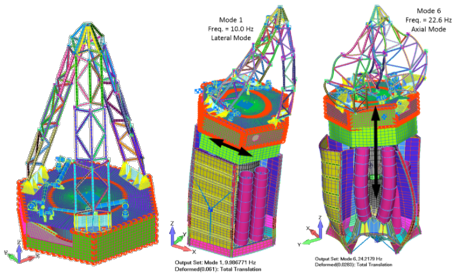
Note: Asteroid operations timeline varies depending on target asteroid. Times shown are for 2008 EV_5: total stay time of 305 days with 95 days of margin.



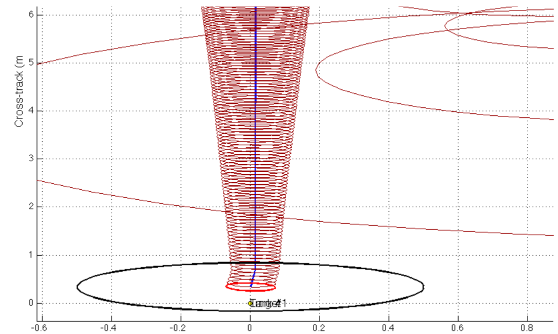
Option B
2014 Analysis and Risk Reduction Activities



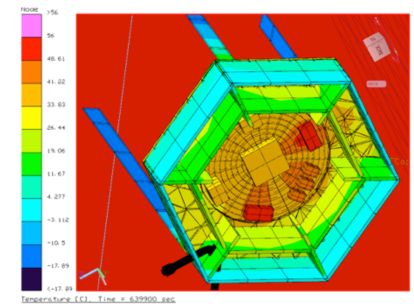
Launch configuration analysis



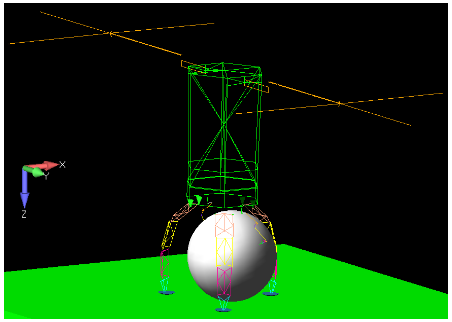
Launch, docking, and EVA modal and loads analyses



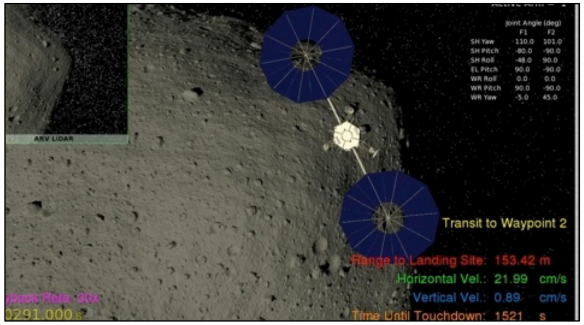
GN&C performance analysis



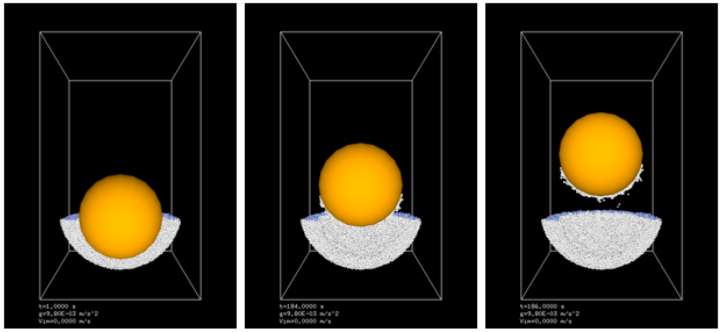
Thermal system modeling



Flexible body dynamics model of touchdown and ascent

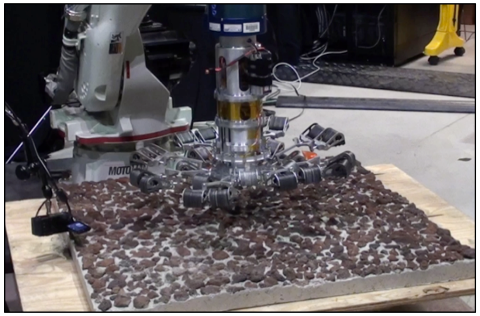


GN&C performance simulation



Boulder extraction simulation

LaRC full-scale CRS flat floor testing



WVRTC/GSFC Microspine testing

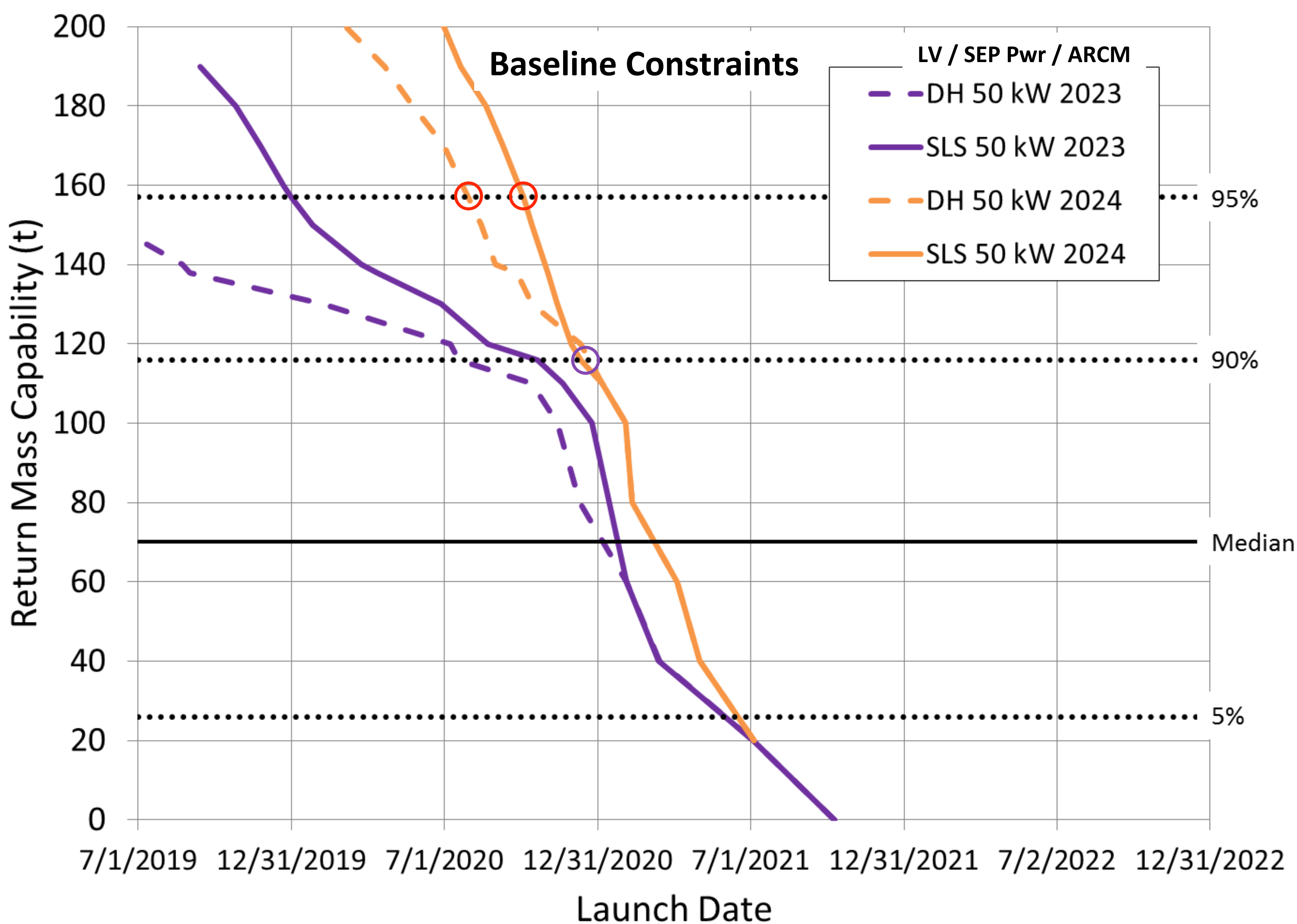
KSC Swamp Works full-scale testing of boulder extraction

Robotic Launch Date Flexibility Assessment: Mission Design

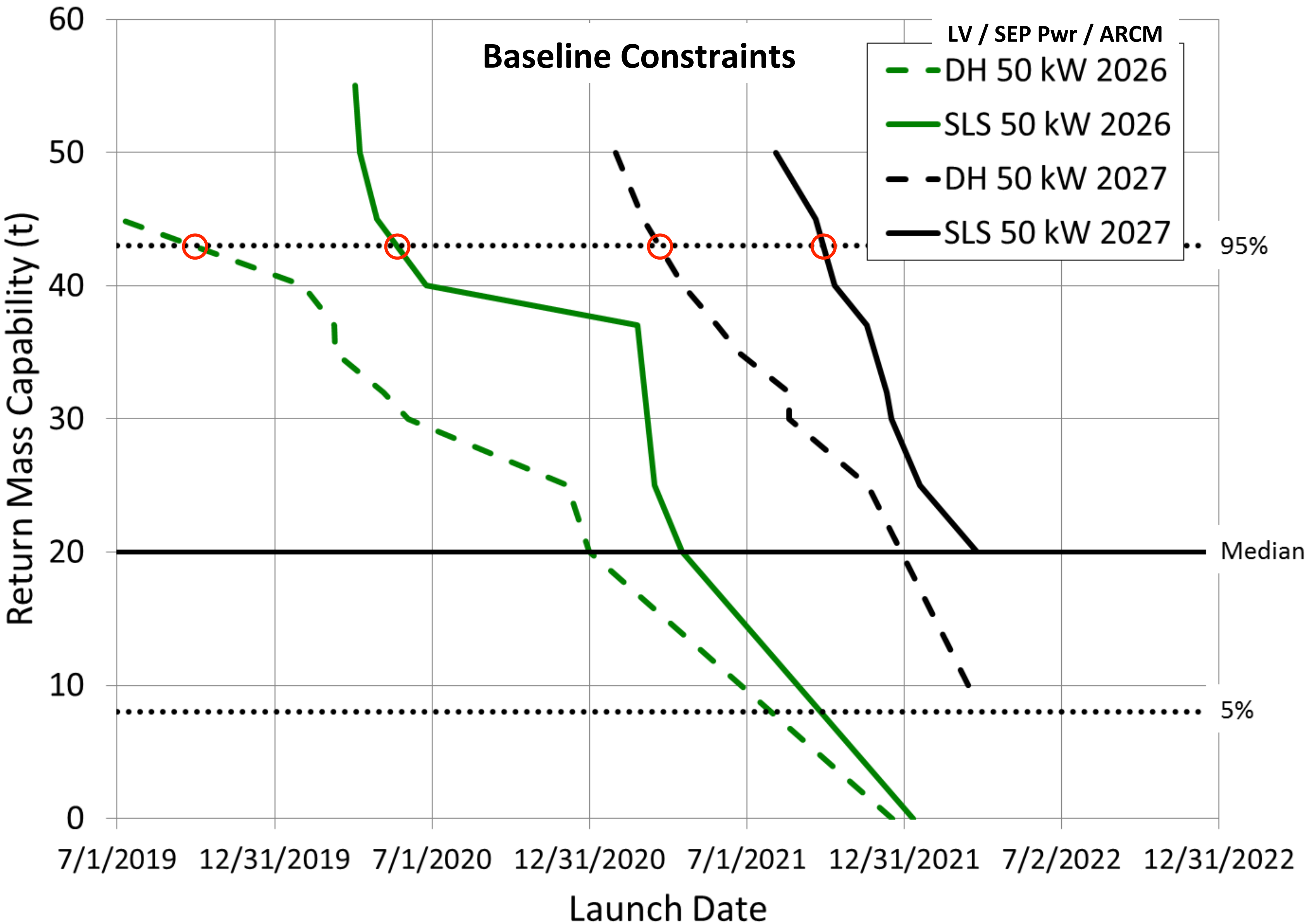
	Option A	Option B
Trajectory Analyses	Create and implement common set of assumptions across both options	
Launch Date Sensitivity	• 95% mass upper bound • Sensitivity to 90% mass	• 95% mass for 2-m boulder • Sensitivity to 1-m boulder
Launch Vehicles	Delta IV Heavy, SLS	
SEP Solar Array Power	50-kW Sensitivity to higher power (82-kW)	
Stay time at Asteroid	60 days	400 days Sensitivity to 215 days
Launch Dates	Mid. 2019 through 2021	
Earliest Crew Accessible Dates	2023 through 2027	

~ 44,000 low-thrust trajectories calculated to explore the trade space

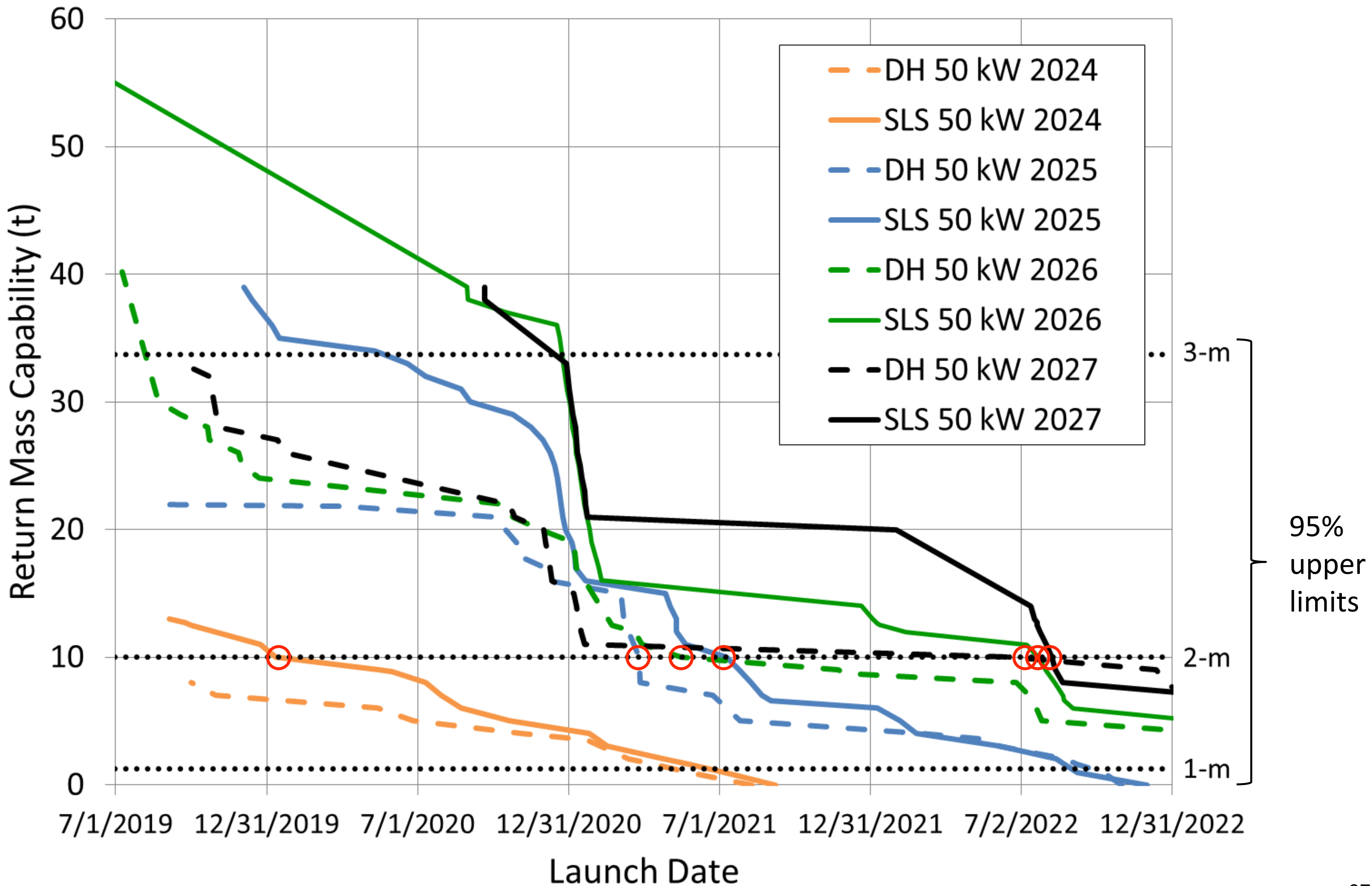
Launch Date Flexibility Example 1 (Baseline Constraints)
Option A: 2023-2024 ARCM with 2009 BD



Launch Date Flexibility Example 3 (Baseline Constraints)
Option A: 2026-2027 ARCM with 2013 EC20



Launch Date Flexibility Example 4 (Baseline Constraints)
Option B: ARCM in 2024-2027 for 2008 EV5



Next Steps

- Complete assessing the budget and complexity differences versus the extensibility advantage in option A/B decision
- Continue asteroid observations and enhancements
- Continue high power, long life solar electric propulsion system technology demonstration activities
- Continue human spaceflight system development and technology maturation
- For selected robotic mission capture concept, refine independent technical risk, schedule and cost assessment.
- Hold Mission Concept Review – scheduled for February 26, 2015